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Co-Combustion of Coal and Alternative Fuels

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1. Introduction

Energy utilization of alternative fuels including biofuels is one of the main tasks for development of recoverable sources in the world. The research consists of combustion tests in the large CFB boilers and measuring data inside the combustor. Since 1995, 29 large CFB boilers of different designs and power outputs have been in operation in the Czech Republic - as shown in the Table 4. Construction of the boilers, technical documentation, licensing and engineering has been based on foreign experience. Every large power project is always preceded by trial measurements and tests on smaller pilot, trial or if need be model equipment. Due to the great difference in scale, some unexpected measuring equipment behavior or problems must be taken into consideration for co-combustion of coal and alternative fuels.

The present research aiming at characterising the co-combustion under-atmospheric fluidized bed conditions by different physical and chemical characteristics has the following objectives:

- Ash formation upon fluidized bed co-combustion.
- Fate of toxic trace metals upon fluidized bed co-combustion.
- Recommendations for suitability of co-combustion in the atmospheric circulated fluidized bed boilers CFB and minimizing the harmful solid and gaseous emissions.

2. Model research

The model research has been carried out at the Technical University of Dresden. It includes the combustion tests - Table 2. - on experimental pilot equipment - Fig. 1. , 2. with atmospheric circulating fluidized bed for coal and bio-fuels produced from the sewage sludge from WWTP (waste water treatment plant) and biomass, and thermo-analytical study of bio-fuels - Table 1. The modelling had the following aims:

- To determine non-uniformity of combustion in the fluidized bed combustor as influencing the composition of flue gases and specification in terms of minor constituents (NO_x , chlorine compounds, alkalis, etc.).
- Analogically the influence of the size or for that matter the influence of fuel granulometric distribution on the process.
- Chemical composition, crystallographic structures, and mechanical properties of combustion solid products (bottom ash, fly ash, deposits).

- Analytical establishment of sulphur forms in fuel and combustion solid products, as well as element analysis for fuel and biomass.
- To perform leaching tests for combustion solid products.
- Detailed study of mineralogical and chemical composition of bottom ash, fly ash, and the solid emission phase in cyclone, heat exchanger and filter. Fig. 3., 4. Table 3.
- Balance for volatile elements, Cl, S, Hg, Se, semi-volatile elements, V, Ni, Co, As, and some non-volatile elements, Cr a Sn. Based on these balances to calculate the content of these elements in emissions and compare with the results of balance measurements.



Fig. 1. General view on pilot plant

Laboratory studies were focused on a detailed identification of input raw materials (coal, biofuel, limestone) so that the measurements could be reproducible: 1. Raw material input analysis and dependence of combustion solid residues on raw material input. 2. Combustion inaccuracy assessment in actual unit condition (T, gaseous and solid components, velocities, modelling). 3. Balance of combustion elements choice, studying mechanisms of deposit formation and composition. 4. Verifying a redistribution model for a choice of elements between the fuel and solid by-products.

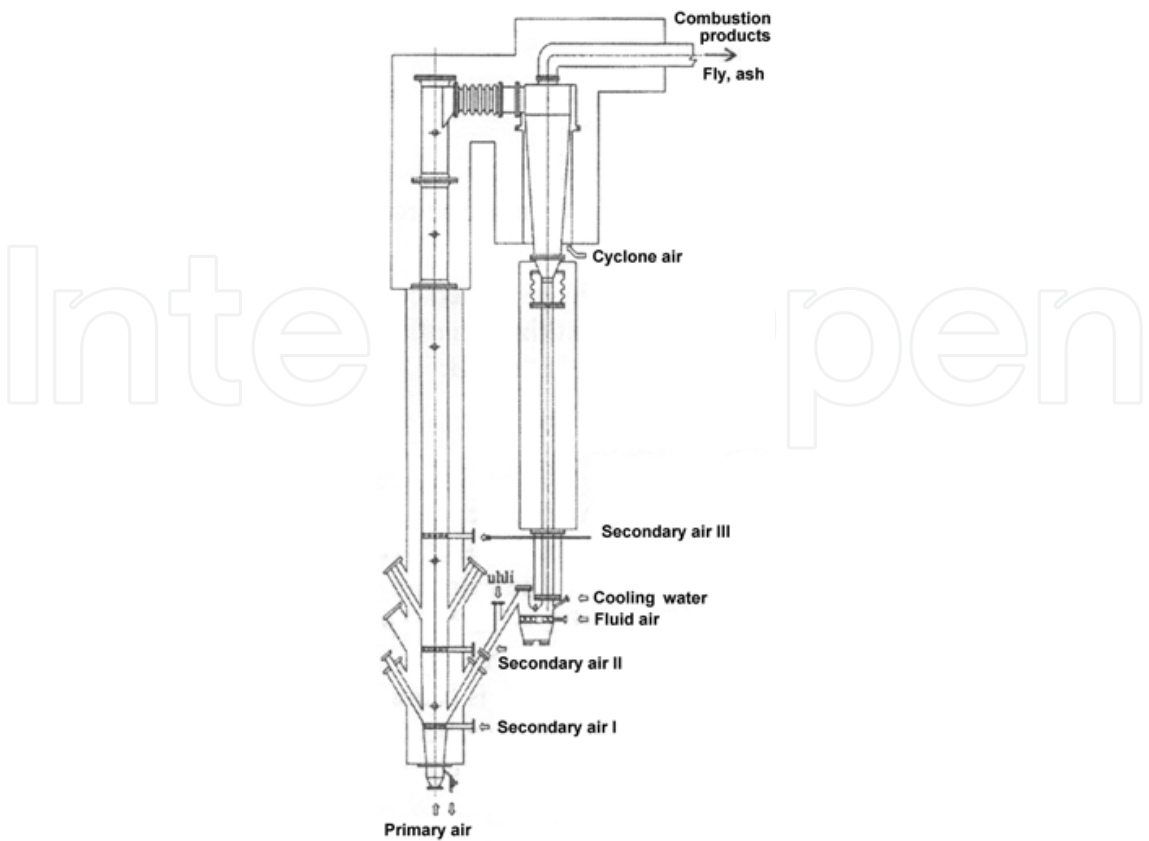


Fig. 2. CFB boiler 300 kW

	Coal	Bio fuel	Water	Ash	C	H	N	S	Volatile combustible	Heating value
	%	%	%	%	%	%	%	%	%	kJ/kg
Brown coal	100	0	14.0	5.2	55.0	3.86	1.03	0.70	45.8	20,599
Mixture	75	25	13.9	8.0	50.4	3.83	1.04	0.65	47.4	18,749
Mixture	50	50	12.6	11.9	45.2	3.79	0.92	0.54	50.6	16,728
Mixture	25	75	12.9	14.0	42.3	3.73	1.08	0.47	51.9	15,688
Biomass	0	100	14.6	13.7	36.6	4.31	1.34	0.24	57.8	13,291

Table 1. The analysis of the fuel mixture

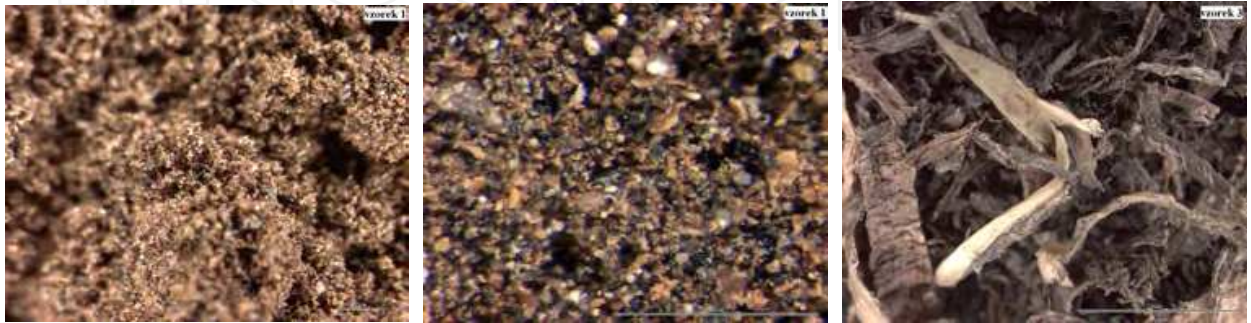


Fig. 3. Scanning electron microscopy (SEM) of combustion residues during experiment - 85 % coal/15 % biomass. Sample 1 - fly ash from heat exchanger. Sample 3 - mixture of biofuel

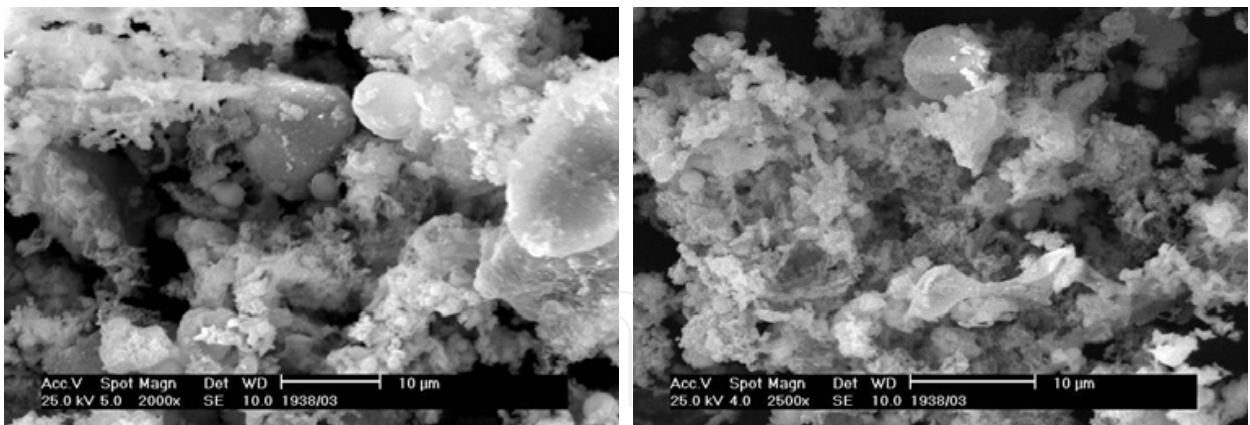


Fig. 4. Scanning electron microscopy-morphology. Sample 85/15-filter, enlargement 2000x. Sample 85/15-filter, enlargement 2500x

Test	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Coal/biomass M _{pal} amount of fuel	100:0% mass 126 kg brown coal	75%:25% M _{pal} = 132kg	50%:50% M _{pal} = 159,3kg	25%:75% M _{pal} = 180kg	85%:15% M _{pal} = 135kg	0%:100% M _{pal} = 203kg
Fuel delivery	42 kg.h ⁻¹	44 kg.h ⁻¹	53,1 kg.h ⁻¹	44 kg.h ⁻¹	42 kg.h ⁻¹	67.7 kg.h ⁻¹
Thermal output	240.3 kW	229.2 kW	246.7 kW	261 kW	222.2 kW	250 kW
Temperature in fluid bed	870 °C	850 °C	850 °C	804 °C	886 °C	800 °C
Content of the flue gases	O ₂ = 3.2%	O ₂ = 5.0% CO = 201ppm SO ₂ = 260 ppm NO _x = 197 ppm	O ₂ = 1.6% CO = 1 887 ppm SO ₂ = 714 ppm NO _x = 191 ppm	O ₂ = 1.9% CO = 1 842 ppm SO ₂ = 950 ppm NO _x = 215 ppm	O ₂ = 2.8% CO = 577 ppm SO ₂ = 967 ppm NO _x = 195 ppm	O ₂ = 3.3%
Excess of air	1.18	1.32	1.083	1.1	1.154	1.189
Unburned C in fly ash	0.051	0.035	0.042	0.086	0.0828	0.047
Velocity in reactor	4.25 m.s ⁻¹	4.50 m.s ⁻¹	4.50 m.s ⁻¹	3.30 m.s ⁻¹	4.24 m.s ⁻¹	4.73 m.s ⁻¹

Table 2. Basic characteristics of the combustion tests

Sample		heat exchanger 85/15	Filter 85/15	Filter 0/100	Cyclone 0/100-wet	Cyclone 0/100-dry
As	result	11.6	11.4	9.1	7.6	10.3
	insecurity	0.6	0.6	0.5	0.4	0.6
Ba	result	900	1,120	1,480	780	920
	insecurity	60	70	90	50	60
Cd	result	8	13	13	6	7
	insecurity	5	7	7	3	4
Co	result	< 20	< 20	< 20	< 20	< 20
Cr	result	149	110	97	285	285
	insecurity	9	7	6	18	18
Cu	result	180	147	200	96	108
	insecurity	13	11	14	7	8
Hg	result	< 5	< 5	< 5	< 5	< 5
Mn	result	1,510	1,810	1,400	1,110	1,150
	insecurity	70	80	60	50	50
Mo	result	< 20	< 20	< 20	< 20	< 20
Ni	result	105	78	69	201	201
	insecurity	7	5	5	13	13
Pb	result	80	82	101	61	75
	insecurity	6	6	8	5	6
Sn	result	100	68	68	59	66
	insecurity	20	14	14	12	14
V	result	52	42	61	49	50
	insecurity	5	4	5	4	5
Zn	result	610	1,080	1,400	550	660
	insecurity	40	70	90	40	40
Loss of annealing	Result in %	16.8	8.47	5.55	6.25	0.57
	Insecurity in %	0.2	0.09	0.06	0.07	0.01

Table 3. Concentration of heavy metals in pilot plant - test No.5., 6 by X-ray fluorescence spectroscopy (mg.kg⁻¹)

The model research verify if the alternative fuel produced from biomass and sewage sludge may be used as alternative energy source in respect of the EU legislation, and/or its other modifications (with additives, decontamination technologies) for suitable fuel, which would comply with emission limits or the proposed energy process optimizing the preparation of coal/sludge mixture for combustion in the existing power engineering equipment.

The limiting factor for sewage sludge utilization from WWTP (waste water treatment plant) in agriculture is the increased content of risk elements and also the occurrence of organic pollutants – primarily polyaromatic hydrocarbons, PCB (polyaromatic byfenyls) and AOX (adsorbable organic halid). Other alternative fuels have not these limiting conditions. The limiting factor for sludge combustion at incineration plants is water content. With regard to the fact that from 2005 the EU Directives EU expects to ban waste disposal sites with any material with content of organic substances above 10 %, it is apparent that the priority condition for sludge utilization is sludge decontamination or power engineering utilization (Loo & Kopperjan 2008). Results from tests may be evaluated as very good with the prerequisite for utilization, testing of investigated substances in real combustion units. On the basis of carried out laboratory and pilot tests one may expect good results from these real units (equipment with greater output), many of these experiments have been already performed. From the results of experiments and thermoanalytical studies it is clear that 15 % of alternative fuels – biofuels based on sludge and brown coal can be used in the large fluidized bed boilers located in the Czech Republic. The combined combustion will enable to fulfil the Czech Republic's pledge to the European Commission concerning the development of renewable energy resources by 2010.

3. Diagnostic methods for operating surveillance of large fluidized bed boilers

Once large units are put into operation during co-combustion of alternative fuels and coal, guaranteed-performance tests must be conducted. The aim of the guaranteed-performance tests is to verify design parameters. Guaranteed-performance figures are compared with reality. Apart from basic measurements there are a number of other similar measurements of specific equipment parts that might be initiated because: the manufacturer is interested in using the experience to improve or design new units and the operator is interested in both eliminating problems and improving the economics of the operation process - Table 4. (Čech 2006). This chapter reviews the development of verification methods and presents some equipment for the determination of all important and interesting measuring data. The conclusions might be useful to energy companies and operators that want to verify operation data of fluidized bed boilers, flue gases and air channels.

Diagnostic measurements at a particular unit basically cover:

- The measurement of fluidized bed temperatures, furnace temperatures, flue gases temperatures at ancillary heating surfaces up to the boiler.
- The measurement of flue gas velocity in the furnace chamber and exits of cyclones, in cyclones, at the cyclone exit to second pass as well as in the area of additional boiler surfaces, sampling of flue gas in the boiler.
- Sampling of characteristic solid ash particles including isokinetic sampling to determine solid particle concentrations.

Place	Year	Type	No	Tph	Producer	Fuel	System
Třinec	1995	CFB	1	160	Lurgi (SES Tlmače)	HC, BIO	ABB
	1997	CFB	1	160			Siemens
Poříčí	1996	CFB	1	250	Foster Wheeler (CNIM)	HC/BC	Siemens
	1998	CFB	1	250		BC, BIO	
Tisová	1996	CFB	1	350	EVT (Vítkovice)	BC, BIO	Valmet
	1998	CFB	1	350	LURGI (SES Tlmače)	BC, BIO	Valmet
Zlín	1996	CFB	1	160	Babcock ABB Alstom	HC, BIO	Honeywell
	2000	CFB	1	125	Lurgi (SES Tlmače)	HC	Honeywell
Komořany	1995 - 99	Fluidized bubble bed	10	125	Power International	HC, BIO	ABB Honeywell
Hodonín	1996	CFB	2	170	AEE Austria	Lignit, HC, BIO	Valmet
Ledvice	1998	CFB	1	350	ABB Alstom	BC	ABB
Olomouc	1998	CFB without hot cyclon	1	190	Foster Wheeler (FORTUM)	HC, BC, BIO	Valmet
Štětí	1998	CFB Retrofit	1	220	Foster Wheeler	BC, BIO	Valmet
Ml.Boleslav	1998	CFB	2	140	EVT (Vítkovice)	HC	ABB
Kladno	1999	CFB	2	375	ABB Alstom	HC	ABB
Plzeň	1999	CFB	1	180	ABB Alstom	BC	ABB

HC – hard coal, BC – brown coal, BIO – biomass , Tph – tons steam per hour - output

Table 4. Newly-built fluid boilers with circulating fluid layer in the Czech Republic

3.1 Flue gas elements

Sampling of flue gas elements from the entire boiler can be divided into three groups:

- Sampling of flue gases from the bottom part of the fluidized bed.
- Sampling of flue gases from the boiler second pass up to the exit to the chimney.
- Sampling of flue gases from the boiler furnace, cyclones and cyclone link channels.

To monitor the fluidized bed boiler operation process O_2 , CO , CO_2 , NO_x and SO_2 measurements can be taken. Other elements are usually monitored up to the exit from the separator of solid particles in front of the chimney. Fig. 5. illustrates a cooled sampling probe that might be used to take flue gases samples. The probe has an identical construction to that used for temperature measuring. During exhaustion gas is rapidly cooled down (from 800 °C to approx. 30 °C in cooled probe) so that there is no reaction with any other flammable waste gases. Gas is then sampled to be analyzed in the mobile laboratory. It is always recommended that a cooled probe is used to take samples from the furnace, cyclone and cyclone linking channels – Fig. 6. Sampling of flue gases from the second pass of the boiler occurs at temperatures safely below 800 °C. Thanks to that temperature a larger part of the gaseous sample is not able to oxidize quickly and thus it is possible to use a sampling tube made of stainless steel or sintered corundum, Al_2O_3 . To set concentration (e.g., SO_2), sampling channels must be heated up during the sampling operation so that no reaction with water occurs.

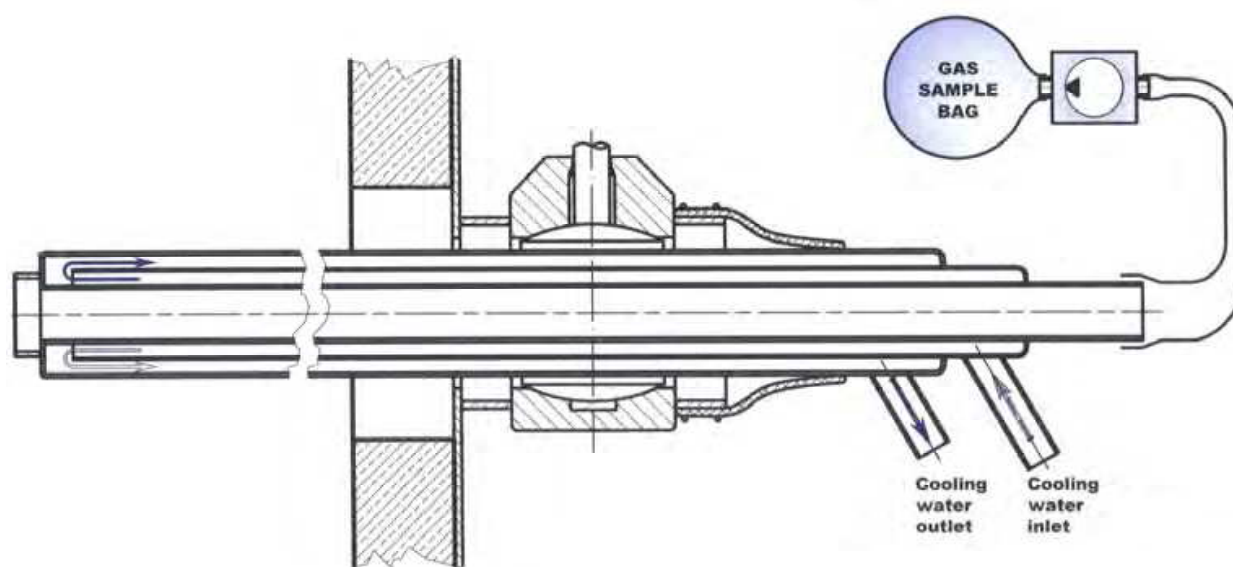


Fig. 5. Probe for flue gas sampling from fluid layer

Fig. 6. illustrates a sampling probe used in the detailed net measuring of O_2 concentration in the boiler combustion chamber with a steam output 125 t/h. (15 % biofuels and 90 % lignite coal).

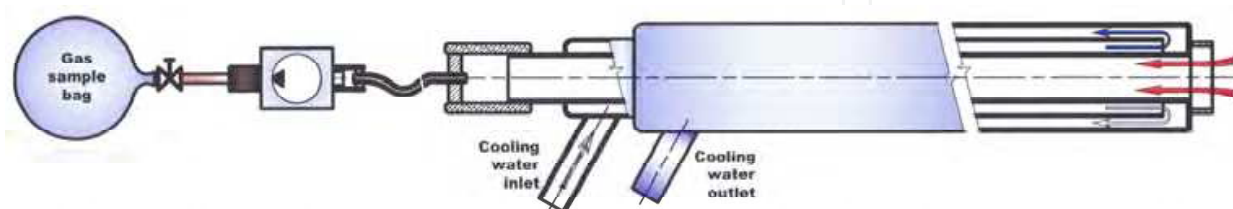


Fig. 6. Probe for flue gas sampling from furnace of boiler

A grid method of measuring O_2 , CO and NO_x concentration was used. Measurements were taken using instrumentation openings in the middle of the side walls of the combustion

chamber. The results of O_2 concentration measurements for 60 % and 90 % nominal output (350 t/h steam) are illustrated in Fig. 7. The results of CO and NO_x concentration measurements for 60 % nominal output are illustrated in Fig. 8.

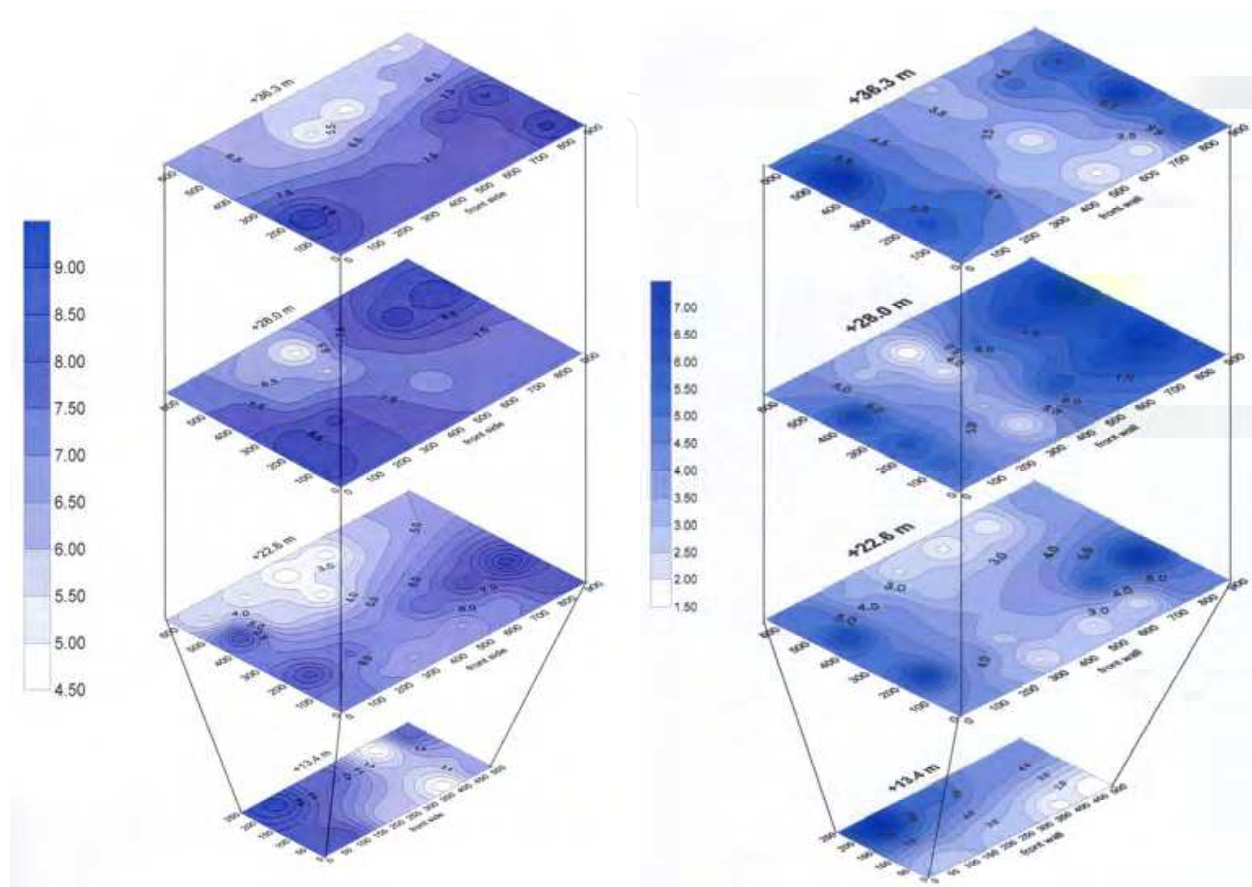


Fig. 7. Results of O_2 concentration measurements by water-cooled sampling probe in relation to height at 60 % and 90 % nominal output during co-combustion tests in power station Tisová.

The measurement results suggest that there is intensive suppression of NO_x formed increases in areas of secondary and tertiary air supply. CO concentration has developed as expected. The concentration decreases if the secondary air supply is gradual.

3.2 Solid particle concentration measurements

To determine the solid particle concentration in air flow, the Czech standard ČSN ISO 9096 needs to be observed. It is gravimetric determination of concentrations based on isokinetic sampling of solid particles from air flow. In the case of fluidized bed chambers the aim is to determine the solid particle concentration in the lower part of the fluidized bed layer and in the boiler furnace. For a bigger or smaller particle separation, the fluidized layer density varies depending on furnace height as well. The density in the lower part is in the range of 500 – 800 $kg.m^{-3}$, in the upper part of the furnace with the circulating layer the range is 0.1-0.5 $kg.m^{-3}$. Pressure in the fluidized layer is always measured for various height levels. The

acquired pressure data are continuously monitored by operation measuring instruments. To determine the solid particles concentration in flue gases, the gravimetric method with solid particles isokinetic sampling can be used. Fig. 9. illustrates the measurement unit for solid particle isokinetic sampling.

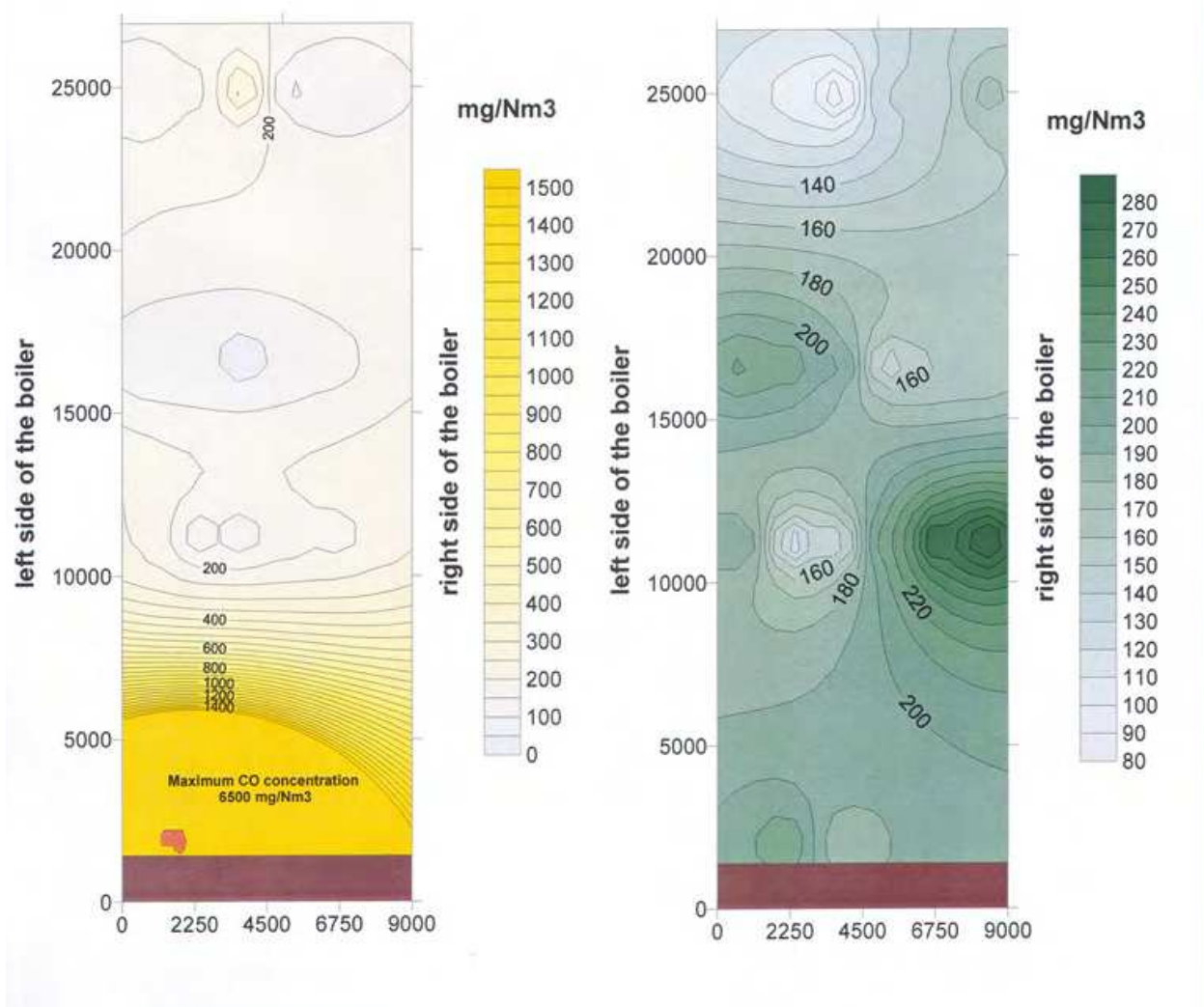
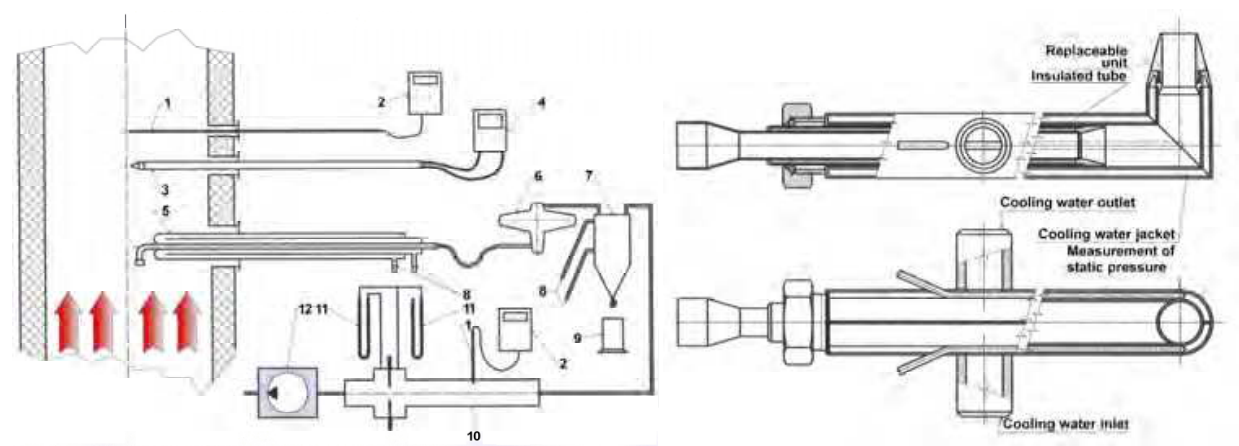


Fig. 8. Average CO and NO_x concentration distribution along the height of the combustion chamber of the boiler at 60 % nominal output in Power station Tisová.

To determine the concentration at the measuring points, a disposable sampling probe is used. Another option would be a sampling probe with cooled support as illustrated in Fig. 10. This probe was developed to measure solid particles through an opening in the membrane wall flag. The sampling device touches the cooled parts only with smaller part to prevent gases from cooling below the dew point during the sampling process. The results of measurement of the solid particle concentration are illustrated in Table 5. for the 100 %, 70 % and 40 % nominal outputs for 15 % biofuel and 90 % lignite. (Power station Tisová 350 t/h steam, 9,42 MPa/ 505 °C). The circulation number is quite high but it corresponds with the very low content of combustible particles measured in chutes under the cyclones. The results of cyclone efficiency measurements for various boiler outputs are from 96,5 % to 98,7 % for right and left cyclone. Generally we can say that hot cyclones of fluidized bed boilers have high separation ability.



Thermocouple 2. Digital thermometer 3. Cylindrical probe 4. Digital pressure sensor 5. Disposable probe for isokinetic sampling 6. Separator 7. Steam condenser 8. Cooling water inlet and outlet 9. Bottle 10. Measuring equipment 11. U tube manometer 12. Air pump

Fig. 9. Diagram of measurement unit for solid particle isokinetic sampling.

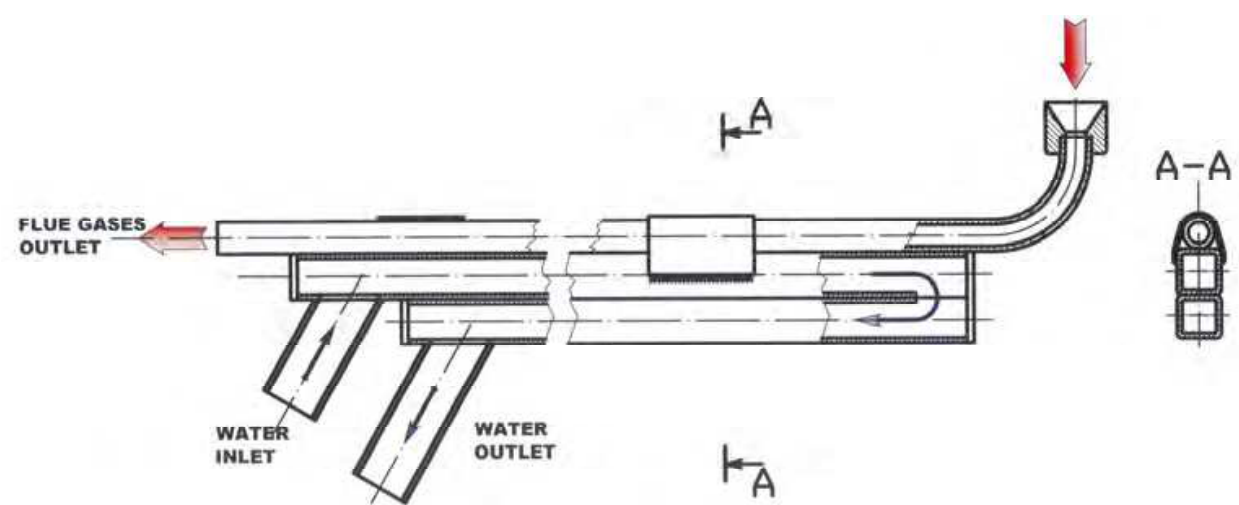


Fig. 10. Sampling water-cooled probe

Boiler output	40 %	70 %	100 %	
Medium concentration of solid particles – left side	841.9	3 308.5	4,427	[g.m ⁻³ _N]
Medium concentration of solid particles – right side	670.1	1,165.7	1,827	[g.m ⁻³ _N]
Mass flow of solid particles – left side	31.21	173.6	234.9	[kg.s ⁻¹]
Mass flow of solid particles – right side	20.14	65.91	100.12	[kg.s ⁻¹]
Total mass flow of solid particles	51.35	239.51	335.02	[kg.s ⁻¹]
Lower heating value	11,860	11,950	11,870	[kg.s ⁻¹]
Fuel consumption	10.041	16.72	23.283	[kg.s ⁻¹]
Volume of ash and limestone supply to boiler	2.447	5.677	6.995	[kg.s ⁻¹]
Circulation number of solid phase – left side	42	81	77	[1]
Circulation number of solid phase – right side	27	31	32	[1]
Circulation number of solid phase through cyclone	34.5	56	54,5	[1]
Distribution of bed ash and light ash	40:60	25:75	13:87	[%]

Table 5. Determination of the circulation number at different boiler outputs

4. Co-combustion of coal and solid waste fuels

Substitution of conventional fossil fuels (like bituminous coal or lignite) by low-carbon fuels for the energetic use is an efficient and cost-effective means of meeting the Kyoto Protocol establishing greenhouse emission targets for each of the participating developed countries (related to their 1990 emission levels). Considerable reductions of CO₂ emissions can be achieved by combustion of waste; therefore combustion of waste materials of various origins (industrial, agricultural etc.) or their co-combustion with fossil fuels in fluidized bed boilers became a legitimate alternative to conventional coal combustion. Another reason why particular attention is paid to energetic utilization of wastes is also elimination of waste and minimizing costs of waste deposition. (Loo & Kopperjan 2008).

But there are still challenges to be solved such as behaviour of the mineral matter during the wastes' combustion. Although the elemental behaviour during coal combustion has been studied and described in detail, the works dealing with redistribution of elements during waste combustion are quite rare, nevertheless, the conclusions described in these works are rather analogous – the application of the results obtained for the coal combustion on the combustion of wastes is not possible since the character of these materials is quite different. (Bartoňová et al., 2008). Another problem is that even if the waste materials differ from one another in their characteristics and content of toxic elements, most works only focus on wood and bark combustion.

This chapter intends to shed more light on the spectrum of alternative fuels used for energy production focusing on the evaluation of the effect of co-combustion of waste fuel and coal on the environment. In the circulating fluidized bed power station in Tisová - 350 t/h – Table 4., the waste alternative fuel (WF) containing plastics (1-20 %), fabric and carpets (45-75 %), rubber (5-15 %), paper (1-10 %) and wood (1-10 %) was co-combusted with the coal and the limestone. The samples of coal, limestone, bottom ash and fly ash were collected at regular time intervals and unburned carbon particles were separated from bottom ash by hand. Analysis of major, minor and trace elements was performed by X-ray fluorescence spectrometry (SPECTRO XEPOS) and mineral analysis was carried out using X-ray diffraction analysis (BRUKER D8 ADVANCE). Ash content of the samples was determined at 815°C. The distribution of macro pores was determined by means of mercury porosimetry (Micromeritics – AUTOPORE IV); SORPTOMATIC 1990 (Thermo Finnigan) equipment was used for the determination of specific surface area and mezopore-size distribution. Scanning electron microscope micrographs were taken by SEM PHILIPS XL – 30.

4.1 Mineral analyses

The X-ray diffraction patterns were obtained for the samples of unburned carbon (UC), bottom ash (BA) and fly ash (FA) Fig. 11. With the aid of elemental analyses of unburned carbon and ash samples the major mineral phases were established in the diffraction patterns and are marked with abbreviations explained in the figure caption. Coal has already been given in indicating the dominant occurrence of quartz and kaolinite. Diffuse area observed in the unburned carbon diffraction pattern (approximately from 25° to 31°) corresponds with semi-crystalline carbon phases. Somewhat lower crystallinity (broadened peaks) is evident also in case of magnetite and calcium hydroxide. Conversely, high-degree crystalline levels are represented e.g. by sharp peaks of quartz,

lime or anatase. The comparison of the diffraction patterns revealed nearly the same mineral composition obtained for both unburned carbons – the dominant mineral phase in both samples was quartz and minor occurrence of anatase was identified as well. The both bottom ashes showed the similar mineral composition as well – it was lime there that was the most abundant mineral phase and also minor amount of quartz, anhydrite and anatase was identified in these samples. The similar mineral composition was obtained also for both fly ashes where quartz was the most dominant mineral and where the occurrence of lime, anhydrite, anatase and calcite was of minor significance. Hence, it can be concluded that the addition of solid waste fuel to coal during the combustion did not change the mineral composition of both unburned carbon and the ash samples. (Bartoňová et al., 2009).

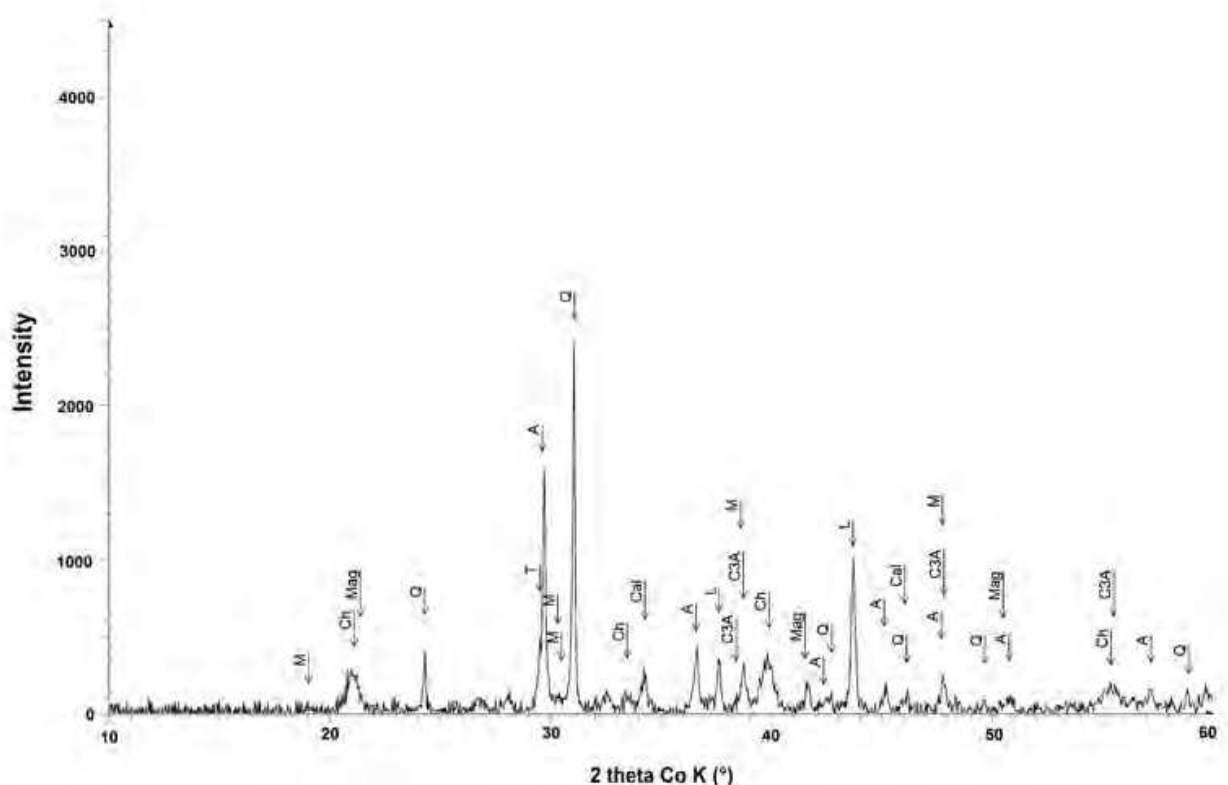


Fig. 11. X-ray diffraction patterns of fly ash (C). Q-quartz, L-lime, Cal – calcite, A – anhydrite, Mag – magnetite, C3A – tricalcium aluminate, Ch - calcium hydroxide, M - mullite T – anatase

4.2 Chemical analyses

By means of X-ray fluorescence spectrometry the contents of major, minor and trace elements were determined in coal (C), unburned carbon (UC), bottom ash (BA), fly ash (FA) and waste alternative fuel (WF). These results as well as the ash contents in these materials are given in Table 6. The porosity of the coal and bottom ash is rather low, whereas unburned carbon shows highly-developed system of ruptures, pores and cavities leading to high porosity of this material. That is why unburned carbon is being studied in relation to its adsorption properties.

4.3 Surface morphology and pore-size distribution

The morphology of coal, waste fuel, unburned carbon and bottom ash grains was studied using scanning electron microscopy with the secondary-electron beam method. The surface structure of coal and waste fuel was determined and the texture of a typical grain of unburned carbon and bottom ash is shown in Fig. 12, 13. A general view (with magnification of 50x) and a surface detail (with magnification of 1500x) are shown for each material studied.

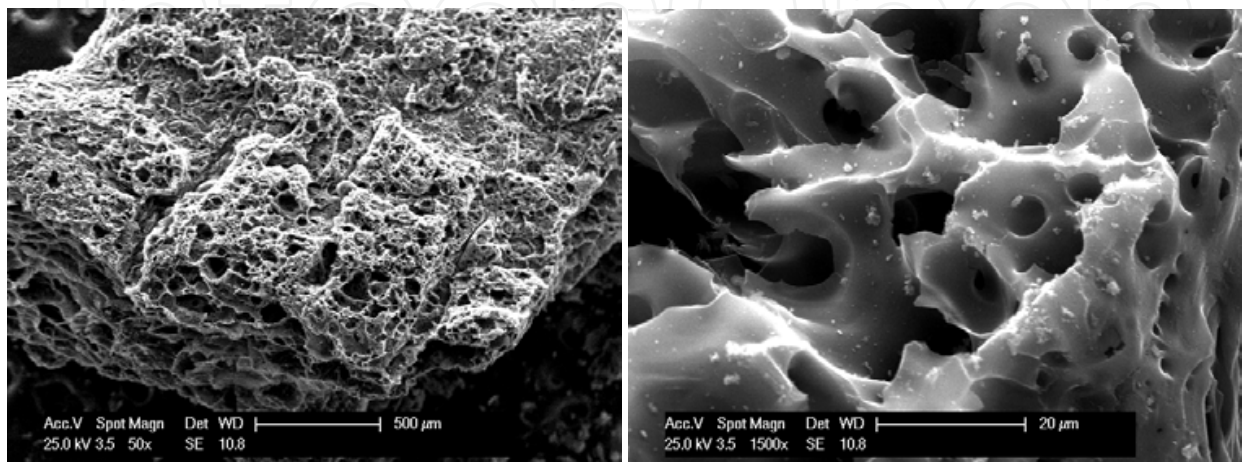
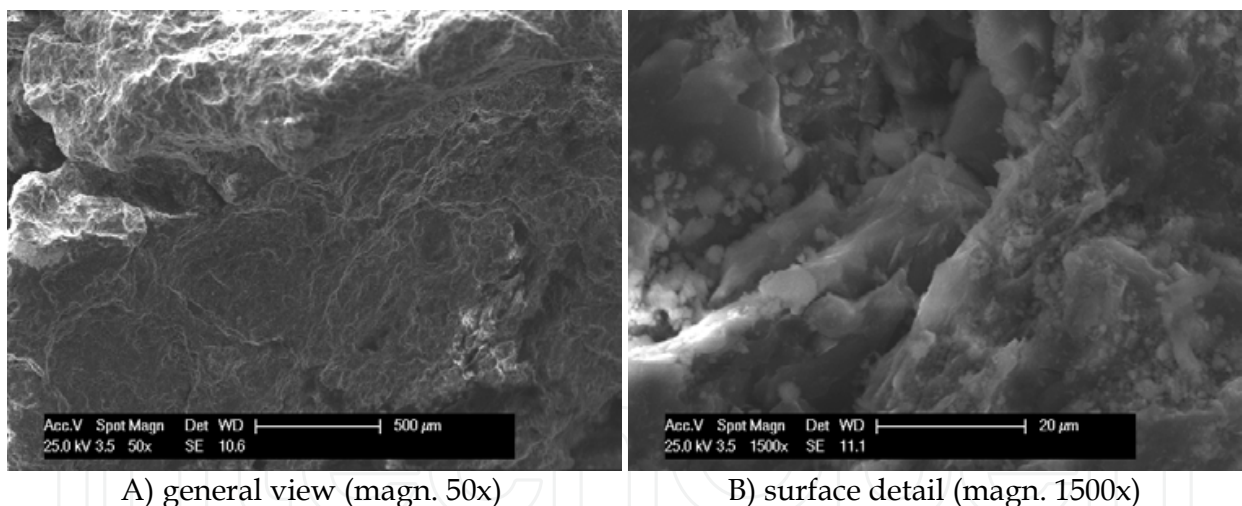


Fig. 12. SEM micrographs of unburned carbon particle



A) general view (magn. 50x)

B) surface detail (magn. 1500x)

Fig. 13. SEM micrographs of bottom ash

The surface texture shown in Fig. 12., 13. indicates that the porosity of unburned carbon collected at waste fuel co-combustion with coal is much better developed than that of unburned carbon when pure coal without waste fuel was combusted. But some caution is needed in such conclusions due to somewhat low representativity of one studied grain towards the average unburned carbon sample. Therefore pore-size distribution and specific surface area measurements were conducted in order to prevent misinterpretation when comparing adsorption properties of unburned carbon collected during pure coal combustion and during co-combustion of coal and waste fuel. Specific surface area of unburned carbon collected at pure coal combustion was 194 m²/g, whereas during co-combustion of the same

coal with waste fuel the specific surface area of unburned carbon reached 297 m²/g, which is significantly higher value. This work was focused on the comparison of minor and trace elements behaviour during the co-combustion of coal and waste alternative fuels with the previous results regarding the combustion of the same pure coal in the same power station but without the added waste fuel. Elemental behaviour exactly in the combustion chamber did not change noticeably when waste alternative fuel was co-combusted with the coal. Even the most abundant elements in waste alternative fuel (related to coal) - Zn, Cl and Br - showed nearly the same behaviour. This observation can be explained through similar high volatility of these elements both in the coal and in the waste materials. (Bartoňová at al., 2009).

Measured contents w _i					
Element	Sample				
	C	UC	BA	FA	WF
Ash (%)	23.4	67.7	98.0	98.8	5.6
Na ₂ O (%)	< 0.2	< 0.2	< 0.3	< 0.3	< 0.1
MgO (%)	< 0.1	< 0.1	0.3	0.6	< 0.02
Al ₂ O ₃ (%)	5.9	21.4	11.6	17.6	0.6
SiO ₂ (%)	11.8	37.3	21.0	30.9	3.9
P ₂ O ₅ (%)	0.1	0.3	0.16	0.3	0.08
K ₂ O (%)	0.1	0.4	0.5	0.4	0.07
CaO (%)	0.7	1.5	44.0	29.8	2.4
TiO ₂ (%)	1.5	5.0	3.0	4.9	0.14
MnO (%)	0.02	0.04	0.10	0.04	0.003
Fe ₂ O ₃ (%)	1.5	4.2	6.1	5.4	0.1
S (%)	1.1	0.7	3.1	2.7	0.1
V (ppm)	62.4	270.0	72.0	233.0	< 6.4
Cl (ppm)	41.5	72.8	87.4	411.0	121.4
Ni (ppm)	12.5	33.0	23.2	75.5	26.4
Cu (ppm)	67.0	176.8	82.2	185.0	25.0
Zn (ppm)	26.6	43.1	111.0	370.3	1717.0
Ga (ppm)	14.4	30.0	21.7	40.1	< 1.0
Ge (ppm)	5.4	11.4	7.4	15.9	1.1
As (ppm)	39.0	27.0	66.0	97.8	< 0.7
Se (ppm)	1.2	2.1	1.6	8.3	0.5
Br (ppm)	1.8	1.2	2.1	12.2	49.1
Rb (ppm)	11.4	39.9	35.2	30.1	< 0.6
W (ppm)	19.1	52.5	21.8	60.2	< 8.1
Pb (ppm)	6.9	22.2	18.2	36.0	1.46
Th (ppm)	5.7	14.4	8.9	17.4	< 1.0

Table 6. Ash contents and concentrations of elements in coal (C), unburned carbon (UC), bottom ash (BA), fly ash (FA) and waste fuel (WF)

Comparison of elemental contents in bottom ash and fly ash was performed to describe further behaviour of elements when leaving the combustion chamber. It was established that when waste fuel was co-combusted with coal, a slight shift towards the higher enrichment of most elements in fly ash (vs. bottom ash) was observed. This trend is the most significant in case of Zn, Cl and Br which are the very elements that were the most abundant in waste fuel (when compared to coal). Therefore it can be concluded that the elements showing high concentrations in waste fuel tend to concentrate in fly ash. Specific surface area of unburned carbon collected at the test where waste fuel was co-combusted with the coal (297 m²/g) was significantly higher than that of unburned carbon from the combustion test without waste materials (194 m²/g). Comparison of pore-size distribution curves obtained for both unburned carbons revealed that unburned carbon collected during coal and wastes combustion contains larger amount of small pores, whereas macropores are more abundant in the unburned carbon from coal combustion without the waste alternative fuel. The unburned carbon collected at the co-combustion of the coal and wastes is undoubtedly of better adsorption properties.

5. Co-combustion of coal and waste wood

Biomass represents a lot of various materials, either waste materials or special energetic plants. Fuels based on wood biomass (sawdust, shavings, chips, tree-bark) can be used also for the production of high-quality biofuels, such as wooden briquettes and pellets, or can be co-combusted with coal. (Bartoňová et al., 2008). Average ash content of wood is about 1 – 2 % and calorific value ranges from 11 to 18 MJ.kg⁻¹. Straw is another advantageous energetic source and its calorific value ranges from 17.6 to 18 MJ.kg⁻¹, ash content is about 5.3 – 7.1 % and is often used e.g. in Sweden, Denmark or USA. (Loo & Kopperjan 2008). The disadvantages of this material are its huge volume and heat-exchanger fouling problems. There are also other biomass materials used for the energetic utilization – various agricultural residues (green wastes, hull, shells, pruning, rice straw, rape residues, corncobs and stems, sugar cane trash, cassava rhizome) as well as growing energetic plants. (Winter & Hofbauer, 1997). This chapter mainly evaluates the environmental impact of fluidized bed combustion of different fossil and biomass fuels. Particular attention was paid to the comparison in the release of environmentally most significant molecular species – amount of solid coal combustion products and their leaching behaviour or emissions of sulphur and carbon dioxide. For this work the samples from circulating fluidized bed power station in Štětí - Table 4. - were collected. In this power station coal combustion and co-combustion of coal / wastes tests were performed in circulating fluidized bed boiler at 870°C. Simplified diagram of the combustion facility is given in Fig. 14. In this power station usually lignite is co-combusted with the wood waste (coming from the cellulose production). Usual lignite / wood waste ratio is 10 :1.

5.1 Combustion tests

Three combustion tests were performed – Regime I, II and III. In Regime I lignite and limestone were combusted (in weight ratio of lignite/limestone = 10:1). In regime II lignite, limestone, sawdust and tree-bark were combusted in coal/wood waste ratio of 1:1.76. In regime III wood, sawdust and wood chips were combusted in ratio of 1:0.21:1. (This combustion test was rather unusual because no bottom ash was created and the only solid

output flow was fly ash). Mass flows of input and output materials (BA – bottom ash, FA – fly ash, E_s – solid emission particles) and volume of gaseous emissions ($V_{E,g}$) are summarized in Table 8. The ash and water contents in these materials are given in Table 8. as well. Mass flows relate to undried samples. Proximate and ultimate analyses of input and output materials are given in Table 7.

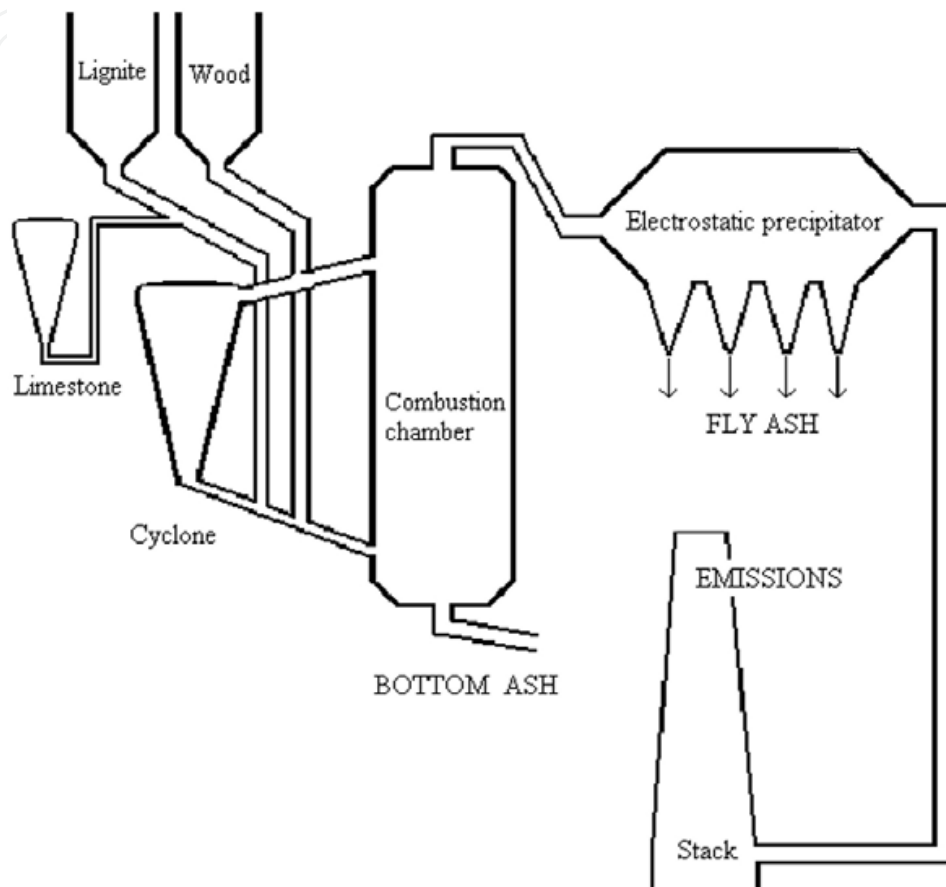


Fig. 14. Simplified diagram of the combustion facility

5.2 Analyses of emissions

Emissions from combustion unit were analysed and CO , NO_x and SO_2 were determined in flue gas, while As, Se, Cd, Hg and Pb were determined in solid particles captured on the filter in flue gas stream. The results of emissions analysis are given in Table 9. In the boiler mantle there are four holes into the combustion chamber. Using these holes as progressive slipping thermocouples to measure temperatures in the fluidized bed at different levels through the holes, where the probe was plugged, three samples of gaseous emissions and ash were collected directly from the fluidized bed. The slipping probe measured temperatures in the fluidized bed at the inlets. All combustion regimes were sampled from storage tanks of fuel and all four sections of the electrostatic precipitator. Furthermore, there was continuous measurement of emissions of NO_x , CO , SO_2 in the flue gases (see Fig. 5). The balance of fuel and combustible waste, the mass flow, moisture content and ash, as well as the mass flow bed ash (BA) and fly ash (FA), the volume of gaseous emissions ($V_{E,g}$), the

quantity of solid emissions, can be evaluated in Table 10. The summary of calculated values shows a relation between the input (m_{inp}) and output (m_{out}) data. The difference between the weights of the input current m_{inp} and output current m_{out} under regime III can be explained by the fluid in the boiler not "running" the whole regime III - cleaning ash from coal combustion and therefore part of the ash has gone into the output stream and so its weight is greater than the output current m_{out} .

Regime	Input	Output
I	Lignite (C): $m_C = 25,920 \text{ kg.hr}^{-1}$ ($W = 14.7 \text{ \%}$, $A = 18.3 \text{ \%}$) Limestone (L) $m_L = 2,630 \text{ kg.hr}^{-1}$ ($W = 0.45\%$, $LOI = 34.1 \text{ \%}$) LOI value in limestone is thought to be CO_2 released during the combustion	$m_{BA} = 3,250 \text{ kg. hr}^{-1}$ $m_{FA} = 3,170 \text{ kg. hr}^{-1}$, $m_{E,s} = 0.42 \text{ kg. hr}^{-1}$ $V_{E,g} = 201,130 \text{ Nm}^3.\text{hr}^{-1}$
II	Lignite (C): $m_C = 11,840 \text{ kg.hr}^{-1}$ ($W = 16.4 \text{ \%}$, $A = 16.8 \text{ \%}$) Limestone (L): $m_L = 970 \text{ kg.hr}^{-1}$ ($W = 0.45 \text{ \%}$, $LOI = 34.1 \text{ \%}$) Sawdust (S): $m_S = 5,220 \text{ kg.hr}^{-1}$ ($W = 28.1 \text{ \%}$, $A = 0.64 \text{ \%}$) Tree-bark (B): $m_B = 5,620 \text{ kg.hr}^{-1}$ ($W = 26.7 \text{ \%}$, $A = 4.8 \text{ \%}$)	$m_{BA} = 2,020 \text{ kg. hr}^{-1}$ $m_{FA} = 1,360 \text{ kg. hr}^{-1}$ $m_{E,s} = 0.57 \text{ kg. hr}^{-1}$ $V_{E,g} = 234,830 \text{ Nm}^3.\text{hr}^{-1}$
III	Wood (W): $m_W = 14,905 \text{ kg.hr}^{-1}$ ($W = 12.8 \text{ \%}$, $A = 0.25 \text{ \%}$) Sawdust (S): $m_S = 3,114 \text{ kg. hr}^{-1}$ ($W = 29.7 \text{ \%}$, $A = 0.47 \text{ \%}$) Wood chips (Ch): $m_{Ch} = 14,870 \text{ kg. hr}^{-1}$ ($W = 26.8 \text{ \%}$, $A = 1.04 \text{ \%}$)	$m_{BA} = 5 \text{ kg. hr}^{-1}$ $m_{FA} = 396 \text{ kg. hr}^{-1}$ $m_{E,s} = 0.16 \text{ kg. hr}^{-1}$ $V_{E,g} = 205,340 \text{ Nm}^3.\text{hr}^{-1}$

Table 7. Mass and volume flows of input and output materials

	Regime I	Regime II			Regime III		
	Lignite	Lignite	Sawdust	Tree-bark	Wood	Sawdust	Wood chips
C (%)	47.84	47.77	33.58	34.43	39.87	32.76	33.02
H (%)	3.98	4.05	4.14	4.26	4.91	3.92	4.03
N (%)	0.88	1.12	0.11	0.50	0.12	0.14	0.27
S _{total} (%)	0.59	0.84	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
O (%)	13.71	13.06	33.43	29.3	42.03	33.03	34.79
W ^a (%)	14.7	16.41	28.12	26.70	12.83	29.71	26.84
A ^a (%)	18.3	16.8	0.64	4.8	0.25	0.47	1.04

Table 8. Proximate analysis of lignite and wood wastes (related to undried samples) for regimes I, II, III.

Input mass flow of carbon converted to carbon dioxide (CO₂): I – 28 kg/h.GW and II-12 kg/h.GW, Table 11. - where the index corresponds to the C carbon in coal - are then calculated giving all the input flows of carbon-converted CO₂. For simplicity it is assumed that all the carbon is burned and transferred to the emissions in the form of CO₂.

	Regime I	Regime II	Regime III	Limits
CO [mg/Nm ³]	17.0	19.9	7.50	250
NO _x [mg/Nm ³]	308	286	150	400
SO ₂ [mg/Nm ³]	294	236	53.81	500
F ⁻ [mg/Nm ³]	-	-	0.9	-
As [mg/Nm ³]	1.29	1.92	1.76	-
Se [mg/Nm ³]	0.10	0.15	0.13	-
Cd [mg/Nm ³]	0.19	0.17	0.25	-
Pb [mg/Nm ³]	0.79	0.85	1.06	-

Table 9. Analysis of emissions for regimes I, II , III and emission limits

	Input (t/h)							Output (t/h)		
	Coal	Lime stone	Saw dust	Bark	Wood	Chips	M _{inp}	FA	BA	M _{out}
I	4,743	1,733	-	-	-	-	6,47	3,21	3,210	6,420
II	1,989	0,640	0,033	0,75			3,41	1,36	2,020	3,380
III	-	-	0,015	-	0,037	0,155	0,20	0,38	0,004	0,390

Table 10. Mass flow of inorganic materials

	Input CO ₂ (t/h)							m _{CO2,out} /Q _p (t/h.GW)
	Carbon	Limestone	Sawdust	Bark	Wood	Chips	m _{CO2,inp}	
I	45,46	0,90	-	-	-	-	46,36	0,20
II	20,74	0,33	6,43	15,70	-	-	43,20	0,16
III	-	-	3,73	-	21,74	18,01	43,48	0,14

Table 11. Calculation of the incoming flow of inorganic materials for 1 GW of power boilers

	Output (kg/h)				% S _{E,g}	m _{s,E} /Q _p (kg/h.GW)
	FA	BA	m _{s,E}	m _{s,out}		
I	102	59	29,6	190,6	15,5	0,13
II	39.0	58.8	27,3	125,5	21,8	0,10
III	13,9	0,1	5,5	19,5	28,2	0,018

Table 12. Output flows of sulphur (S)

The results confirm that burning wood emits less CO₂ to the atmosphere per unit of energy input than burning brown coal. The data listed in Table 12. show that the minimum content of SO₂ emissions (% S_{E,g}) is the combustion of coal with limestone (regime I). Absolute numbers of sulphur contained in the mass emissions (m_{s, E}), however, clearly demonstrate that by burning wood the amount of sulphur getting in the emissions into the atmosphere is

about 10 times smaller than that of burning coal. This parameter is much more favourable for burning wood. The most significant results are summarized below:

- Mass balance calculations suggest that mass flow of inorganic matter produced per 1 GW of boiler output has dropped from 28 kg /hr.GW for lignite combustion to 0.7 kg /hr.GW when wood wastes were combusted.
- This observation is a source of many advantages relating to ash land-filling e.g. decreasing the amount of ashes produced during the combustion process will consequently result in decreased amount of toxic leachates, above all sulphates, and also the increase of pH (due to high amount of Ca-bearing minerals present in coal ash) will not be as significant).
- Mass flow of CO₂ produced during the combustion was related to 1 GW boiler output. 0.20 kg /hr.GW was obtained for lignite combustion and it has dropped to 0.14 kg /hr.GW released when wood wastes were combusted.
- Sulphur emissions were also recalculated to 1 GW boiler output - sulphur emission flow calculated for lignite combustion (0.13 kg /hr.GW) was considerably higher than that obtained for wood wastes combustion (0.01 kg /hr.GW).

In conclusion - the results described above unambiguously suggest that the waste wood combustion produces lower amount of environmentally-hazardous pollutants than fossil fuel combustion, even if combusted with Ca-bearing additives. (Klika 2010).

6. Co-combustion of coal and sewage sludge

The sewage sludge is a heterogenous mixture of organic elements (both live and lifeless microorganism cells) and inorganic elements. The organic part of the sewage sludge is mainly represented by the proteins, sugars and lipids. The inorganic part sustains mainly of the compounds of silicon, ferrum, calcium and phosphorus. Moreover the sludge consist of a wide range of harmful substances as well - heavy metals, persistent organic elements PCB, PCDD/F, PAU etc. and other organic harmful elements. The Table 13. illustrates the summary of the organic polutants in the sewage sludge dry residues taken from the Central Sewage Plant of Ostrava (CSPO) and it is evident that almost all limits of the monitored polutants are exceeded. Such high values prevent the sewage sludge from being used for agricultural purposes and land reclamation - necessitating the usage of both the underground and exterior storage. The biggest problem in this case is the high content of the polyaromatic hydrocarbons that is ten times higher than the allowed limit. It is probably because of the industrial waste-water disposal. The value of TOC (Total Organic Carbon) that does not fit can rather be considered a useful than limiting factor. The energetical content of the sewage sludge is based on the chemical energy of the organic components that are capable of oxidation. To be able to describe the sewage sludge as fuel a material that converts its primary energy into the thermic energy - the condition of being flammable must be met. To make the combustion process balanced it is necessary to achieve fuel efficiencies from dry sludge residues and other heat distributed to the furnace, making it possible to use the water vaporization heat contained in fuel, the heat needed for the superheating of the water vapours in the waste gases and the heat needed for the waste gases heating. The important criterion of keeping the combustion process balanced is thus the water ratio in the sludge. Thus a problem exists because water ratio of the mechanically drained sludge is high (cca. 60 - 80 %) for the relatively low fuel efficiency and therefore the sludge cannot be

combusted by itself. The most important energy characteristic of each single fuel is its efficiency. The dry residue efficiency of the anaerobically stabilized sewage sludge is in the range of 7 – 10 MJ.kg⁻¹. Fig.15. shows the sewage sludge structure.

indicator – sample from the CSPO		Limit value	Rated value
Benzen	[mg/kg] dry residue	0.1	0.135
BTEX	[mg/kg] dry residue	10	5.46
EOX (Cl)	[mg/kg] dry residue	10	11.7
NEL	[mg/kg] dry residue	200	4,840
ΣPAU (15)	[mg/kg] dry residue	10	103
PCB (summary of 6 kongerens)	[mg/kg] dry residue	0.2	0.3
TOC	[%]	20	25.3
Tetrachlorethen	[mg/kg] dry residue	0.5	< 0.030
Trichlorethen	[mg/kg] dry residue	1	0.233

Table 13. Organic polutants in sewage sludge

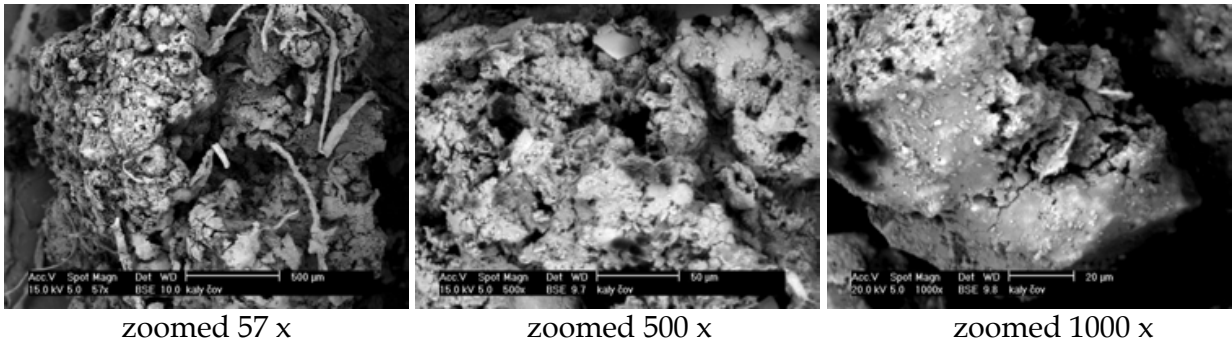


Fig. 15. The structure of the sewage sludge from CSPO

6.1 The combustion test description

The combustion test with the mechanically drained digested sewage sludge (the water proportion in the sludge was approx. 63 %) was carried out at circulating fluidized bed power station in Třinec with an output of 130 MW_t - Table 4. The mixture of hard energy coal and the coal sludge of average efficiency Q_i^r = 19 MJ.kg⁻¹, water ratio W^r = 7,5 %, ash content A^r = 30 % was combusted at the fluid boiler. During the combustion test the fuel was distributed to the boiler in the ratio: 11 %_{weight}-sewage sludge from the Central Sewage Plant of Ostrava, 28 %_{weight}-energy coal and 61 %_{weight}-coal sludge. During the additional combustion of the sludge the mixture characteristics changed as follows: heating value Q_i^r = 17 MJ.kg⁻¹, water ratio w^r = 14,5 %, ash content A^r = 28 %. Based on the fact that the total heating value of the fuel mixture thus dropped by cca 2 MJ/kg during the additional combustion, the volume of the mixture must be enlarged by approx. 0,65 kg.s⁻¹ to maintain the constant boiler output. However the total coal consumption does not raise and this fact is important. The description of the combusted fuel is illustrated in Table 14., 15., and 16. The glory-angle of the mixture was rapidly changed for the worse, compared to the hard coal. The chain feeders of the crude fuel worked reliably and had no failures. Thanks to the

mixture passing through the chain feeder the big pieces of the sludge were crushed. The combustion test showed that 15 % of the sludge content in the mixture was the cut-off amount able to pass the swing-hammer crusher. The moisture was of a fundamental importance concerning the allowable amount of the sludge in the mixture.

Crude form sample			Energy coal	Sewage sludge	Coal sludge
Water ratio	W ^r	[%]	10.23	62.36	6.22
Ash content	A ^r	[%]	24.77	19.52	31.78
Heating value	Q _f ^r	[kJ · kg ⁻¹]	18,854	1,476	18,962
Waterless sample			Energy coal	Sewage sludge	Coal sludge
carbon	C ^d	[%]	59.88	22.50	56.34
hydrogen	H ^d	[%]	3.92	3.48	3.36
sulphur	S ^d	[%]	0.35	0.63	0.22
nitrogen	N ^d	[%]	1.30	2.40	1.21
oxygen	O ^d	[%]	6.96	19.14	4.99
ash	A ^d	[%]	27.59	51.85	33.88

Table 14. The fuel characteristics in crude and waterless form

			Energy coal	Sewage sludge	Coal sludge
carbon	C ^h	[%]	82.70	46.72	85.21
hydrogen	H ^h	[%]	5.42	7.22	5.08
sulphur	S ^h	[%]	0.48	1.31	0.33
nitrogen	N ^h	[%]	1.79	4.99	1.84
oxygen	O ^h	[%]	9.61	39.75	7.55

Table 15. Fuel combustible composition

Sample	SiO ₂ [%]	TiO ₂ [%]	Al ₂ O ₃ [%]	Fe ₂ O ₃ [%]	MnO [%]	MgO [%]	CaO [%]	Na ₂ O [%]	K ₂ O [%]	SO ₃ [%]	P ₂ O ₅ [%]
Energy coal	16.02	0.28	7.2	1.96	0.04	<0.83	0.92	<2.02	0.86	1.6	0.22
Sewage sludge	13.78	0.25	2.49	10.24	0.11	<0.83	13.73	<2.02	0.38	3.35	6.44
Coal sludge	22.46	0.35	9.48	3.26	0.05	<0.83	1.07	<2.02	1.28	1.87	0.24

Table 16. The silicate analysis of the energy coal, sewage sludge and coal sludge (RTG-fluorescence method)

During the combustion test the sludge moisture was approx. 65 % compared to the hard coal moisture of 7, 5 %. The higher moisture makes the temperature drop behind the crusher and it results in sealing the crusher with the mixture of the wet mud.

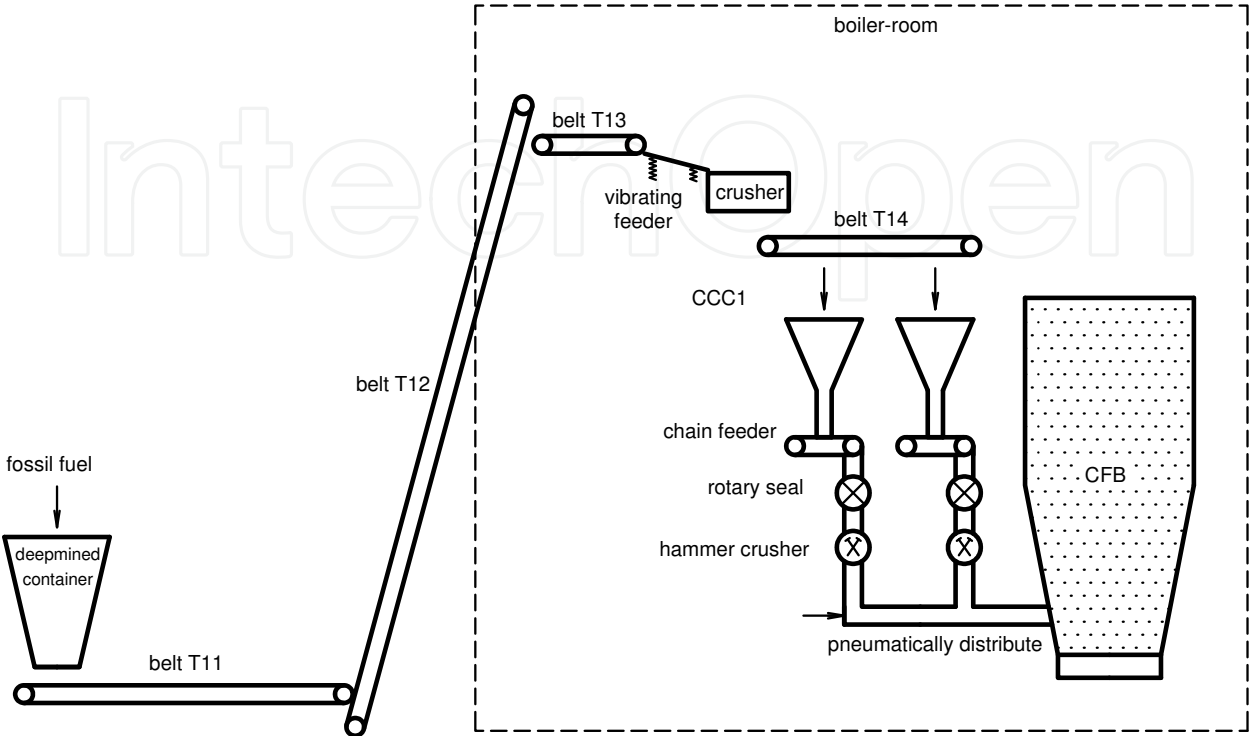


Fig. 16. The scheme of the distribution of the fuel to the CFB boiler

6.2 The boiler efficiency and its operational reliability

Based on the combusted coal and the sewage sludge of given ratio the approx. 0.3 % drop in efficiency of the boiler was observed - Table 17. The content of the combustible carbon in the combustion products corresponds with the fine hard coal combustion.

Fuel	η_k	C_{LP}	C_{UP}
	%	%	%
Energy coal and coal shed	89.1 – 90.5	0.25	6.5
Energy coal, coal shed and sludge	88.8 – 90.2	0.3	5.8

Table 17. The boiler efficiency η_k and the combustible matter content in the ash, where C_{LP} indicates the combustible matter content in the bedding ash and C_{UP} indicates the combustible matter content in the ash

If we focus on the operational efficiency of the boiler under the condition of the additional combustion of the sludge it it is advisable to monitor unwanted states like rust formation caused by high and low temperataure and silting the heat transfer surfaces and abrasion. In the case of boilers with the fluid bed and the additive desulphurisation, the marks of the chlorine

rust pop up even if the chlorine content in the fuel is low. The ratio Cl/SO₂ has an impact on the high-temperature chlorine rust intensity. As for the chlorine content in the fuel sludge, it is evident that it does not exceed the volume found in the hard coal. The HCl concentration in waste gases influence the low-temperature rust intensity. In this particular case the rust rust in the recuperative air heater needs to be considered as well. Another characteristic of the operational efficiency of the combustion equipment is the silting of the heat transfer surfaces. It is important to notice the research on the thermoplastic characteristics of he ash. These characteristics are demonstrated by the following temperatures: t_A – softening point , t_B – melting point a t_C – pour point. The lowest temperature for the mixture of the sludge and coal is approx. 1220 °C for the half-reductive atmosphere.

6.3 The emissions

During the combustion test continuous measurements of the harmful gases like CO, NO_x, SO₂ and relative oxygen behind the boiler. were made by the Technical University of Ostrava. Furthermore single measurements of other emissions like cadmium, mercury, lead, arsen and their compounds, polychlorinated dibenzodioxines PCDD, polychlorinated dibenzofurans PCDF, polychlorinated bipenyls PCB, polycyclic aromatic hydrocarbons PAU, gaseous anorganic chlorine and fluor compounds, hard pollutants TZL, were also by the company TESO Ostrava. The measured values of the pollutants were re-counted to 6 % O₂. The pollutants are illustrated in Table 17. The table provides evidence that the components CO, NO_x, TZL, PCDD/F, HF, Hg meet the requirements of the public notice No. 354/2002 of the Codes of Law but the emissions of SO₂ and HCl do not. This can be attributed to the fact that the sorbent dosing to the boiler was put out of action during the combustion test and thus the process of the conversion of both SO₂ to CaSO₄ and HCl to CaCl₂ could not occur.

emission	unit	Measured concentration	Limit values *)	
NO _x	mg.m ⁻³ _N	80	238	Meets the requirements
SO ₂	mg.m ⁻³ _N	560	333	Does not meet the requirements
TZL	mg.m ⁻³ _N	11	26	Meets the requirements
HCl	mg.m ⁻³ _N	17	10	Does not meet the requirements
HF	mg.m ⁻³ _N	0.2	1	Meets the requirements
PCDD/F	ng(TE).m ⁻³ _N	0.006	0,1	Meets the requirements
Hg	mg.m ⁻³ _N	0.0013	0,05	Meets the requirements

*) ... limit values given by No. 354/2002 of The Codes Of Law.

Table 18. The chosen emissions of the pollutants (6 % O₂, 101,32 kPa, 0 °C)

Regarding the boilers and reducing their emissions of SO₂, the fine grounded lime stone CaCO₃ is continually added directly to the furnace. The lowerig emissions of SO₂ approx. by 100 mg.m⁻³_N was observed during the combustion test with the the shut-down

desulphurisation. This reduction in SO_2 content in the waste gases is obtainable only under the condition of additional combustion of the sewage sludge. The additive gets into the sewage sludge during the process of the sludge hygienisation by the lime dosing at the sewage plant. Furthermore it is hydrated on $\text{Ca}(\text{OH})_2$ by the sludge humidity. The lime hydrate is rid of CaO while entering the fluidized bed boiler. The CaO then reacts with the SO_2 and the CaSO_4 . The amount of the additives in the sludge lowers the lime stone consumption as the primary source (Szeliga 2008). The analysis of heavy metals and microelements in the combusted fuels (the energy coal, the coal sludge, the sewage sludge) were carried out in the laboratories of The Technical University of Ostrava. The evaluation was made for the single coal combustion and then for the mixture of coal and sludge. The redistribution of heavy metals and microelements during the additional combustion of the sewage sludge to the combustion hard residues and the emissions are a matter of further research. The combustion test proves there are further opportunities for additional fuel combustion in the fluidized bed boilers. The advantages of this kind of sewage sludge usage are mainly in the reliable decomposition and oxidation of the organic harmful elements and significant sludge volume reduction. Another suitable way of using the sludge is to reduce its humidity, which improves fuel efficiency, transport and manipulation. The disadvantage of the thermic usage of the sewage sludge is higher concentration of heavy metals and microelements entering the combustion equipment. Co-combustion of coal and sewage is possible only if there is appropriate content of heavy metals in the sewage sludge entering the combustion process. The monitoring and analyses of heavy metals in the sewage sludge are necessary.

7. Findings

The most important findings from the research can be summarized as follows:

1. Stability of combustion depends on two factors: a) regular and uniform feed regulation of the fuel mixture, b) perfect homogenization of the fuel mixture. Otherwise, pulsation in the furnace can occur.
2. Experience with the combustion of sewage sludge showed that the highly volatile matter contents significantly affect the overall combustion process. Care must be taken to achieve complete combustion of the volatiles to ensure higher combustion efficiency and low emissions of CO , hydrocarbons and PAH (polyaromatic hydrocarbons).
3. During devolatilization the biomass undergoes a thermal decomposition with subsequent release of the volatiles and formation of tar and char. The results show that the quantities of char and gas formed depend on the type of carbonised material. Furthermore, increasing the pyrolysis temperature leads to a decrease in the quantity of char formed and an increase in the quantity of volatiles. Analyses of the compositions of the volatiles from straw and stover as well as from wood chips and sewage sludge show that CO , H_2 , CO_2 and CH_4 are the main gaseous components. High moisture contents have been found to increase the devolatilisation time. For dry residues, in addition to the expected immediate ignition and the highly volatile matter contents, the volatiles consist mainly of combustibles – CO , H_2 and C_xH_y .
4. The composition of the ashes from sewage sludge, coal, peat and wood influences melting point. It is known that the Na_2O contents of the residues are low and

- comparable to those of sewage sludge, wood, peat and coal. The K_2O content of the fuel ashes on their melting points is well demonstrated.
5. Combination of low flow rate and high temperature causes the particles, which are coated with fuel ash, to contact each other and form weak physical bonds or to agglomerate. The formation of these weak bonds or agglomeration is due to the surface of the particles having a low eutectic point or ash softening temperature. This low value is caused by the high alkali content, specifically sodium and potassium compounds, formed during combustion of the boiler fuel. The agglomerated particles, subjected to high temperatures, then begin to sinter or stick together through bond densification thereby forming a strong physical and chemical bond.
 6. Agglomeration begins when part of the fuel ash melts and causes adhesion of bed particles. Beginning of agglomeration in the fluidized bed is often indicated by occurrence of temperature differences in the bed and the presence of large fluctuation of bed pressure. When the feeding of the fuel continues it eventually leads to a de-fluidization of the whole bed.
 7. To rate the propensity of fuels against fouling, the alkali index has been developed. This index relates the mass of alkali metal oxides $K_2O + Na_2O$ produced with ash to the GJ of energy generated thermally and may be used for biomass feedstock. Above 0,17 kg alkali/GJ fouling is likely and above 0,34 kg/GJ fouling is virtually certain to occur.
 8. Ash deposition from biomass fuels which contain certain chemicals can also create corrosion and erosion of metals. Two most abundant inorganic elements are Si and K that form silicates with a low melting point. The combustion leads to the condensation of molten silicates which are likely to cause fouling and corrosion. Analyses showed that corrosive reactions occur between chemical compounds in the ash particles and the elements in the metal on un-cooled samples at gas temperatures near 650 °C.
 9. Solutions for the problems resulting from the low melting points of the ash are: use of additives, use of alternative bed materials in the case of fluidized bed combustion and blending of biofuels with coals, lignite.
 10. There are three routes of formation of NO_x during coal combustion, namely: thermal, prompt and fuel - NO_x . Biomass has high contents of volatile matter and low contents of fixed carbon, so that the effect of char on formation of NO_x and N_2O may be significant. However, the catalytic effect of the ash could be important for residues which have high CaO contents.
 11. Concentrations of heavy metals are in compliance with environmental directive of EU2000/76/EG (including cancerous harmful components and benzopyren +Cd+Co+Cr+As). Combustion of alternative fuels and coal has no significant influence to leaching and Ph factor.

8. Conclusion

Since 1996 29 large fluidized bed boilers with desulphurization ability during combustion process have been launched in the Czech Republic. The differences in design and various concepts of these units have helped collect a lot of valuable data and gain a great deal of experience. The opportunity had not existed before these units were constructed.

Because the boilers for co-combustion of coal and alternative fuels in the Czech Republic were developed from know-how of foreign suppliers, it was not possible to get familiarized

with the technical parameters until they started operation. The first operation hours of the most of these boilers were affected by the typical characteristics of Czech coal. Highly abrasive ash matter, high humidity, clay impurity of the fuel and higher content of other elements in the raw fuel (stone, wood, metal) made it necessary to modify fuel feed channels, crushers, separating plants and fuel intake to fluid channels. Many times before, these problems resulted in total unit reconstruction or even replacement. Frequent fuel supply discharges led to reduction of durability of heavy linings of the combustion chamber, especially cyclone bricking and chutes under the cyclones. Some problems were caused by ash extraction from fluidized layer, its cooling down, granulometrics finishing and further manipulation. Other problems occurred in sintering fluidized particles when combustion temperatures were well below 900 °C. In spite of this mass sintering happens in various parts of the boiler. Last but not least, there is a trend to reduce desulphurization costs if the molar ratio Ca/S is in the range of / from 2.5 to 3, which means higher operation costs compared to wet tailings.

A quite new area of fluidized bed boilers is the combined combustion of coal and alternative fuels or the co-combustion of assorted fuels from renewable sources. Despite some slowdown in the expansion of activities in energetics, there are further projects in the area of applied research focused on operation process optimization, efficiency improvements and operation costs minimization. These are the areas where the information obtained from measurement results in various boiler types can be used.

9. Acknowledgments

The author would like to express their acknowledgements to the National Program of Research *ENET* – energy units for utilization of non-traditional energy sources cz.1.05/2.1.00/03.0069 for the financial support of this work.

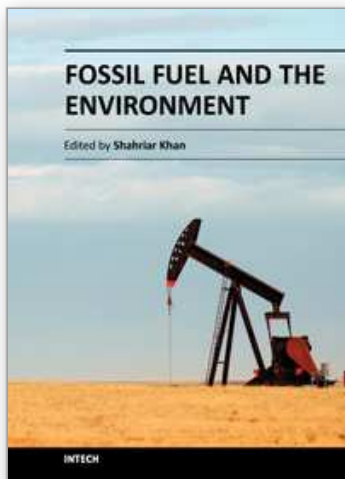
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Fossil Fuel and the Environment

Edited by Dr. Shahriar Khan

ISBN 978-953-51-0277-9

Hard cover, 304 pages

Publisher InTech

Published online 14, March, 2012

Published in print edition March, 2012

The world today is at crossroads in terms of energy, as fossil fuel continues to shape global geopolitics. Alternative energy has become rapidly feasible, with thousands of wind-turbines emerging in the landscapes of the US and Europe. Solar energy and bio-fuels have found similarly wide applications. This book is a compilation of 13 chapters. The topics move mostly seamlessly from fuel combustion and coexistence with renewable energy, to the environment, and finally to the economics of energy, and food security. The research and vision defines much of the range of our scientific knowledge on the subject and is a driving force for the future. Whether feasible or futuristic, this book is a great read for researchers, practitioners, or just about anyone with an enquiring mind on this subject.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Pavel Kolat and Zdeněk Kadlec (2012). Co-Combustion of Coal and Alternative Fuels, Fossil Fuel and the Environment, Dr. Shahriar Khan (Ed.), ISBN: 978-953-51-0277-9, InTech, Available from:
<http://www.intechopen.com/books/fossil-fuel-and-the-environment/co-combustion-of-coal-and-alternative-fuels>

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